Neutron diffraction experiments on ordered silver nuclei at Picokelvin temperatures. A feasibility study

Annila, A.J.; Clausen, K.N.; Hakonen, P.J.; Lindgård, Per-Anker; Lounasmaa, O.V.; Nummila, K.K.; Oja, A.S.; Siemensmeyer, K.; Steiner, M.; Tuoriniemi, J.T.

Total number of authors:
12

Publication date:
1990

Document Version
Publisher's PDF, also known as Version of record

RISØ

Risø-M-2874

Neutron Diffraction Experiments on Ordered Silver Nuclei at Picokelvin Temperatures - A Feasibility Study

A.J. Annila, K.N.Clausen, P.J. Hakonen, P.-A. Lindgård, O.V. Lounasmaa, K.K. Nummila, A.S. Oja, K. Siemensmeyer, M. Steiner, J.T. Tuoriniemi, H. Weinfurter, and H.E. Viertiö

Risø National Laboratory, DK-4000 Roskilde, Denmark
August 1990

Neutron Diffraction Experiments on Ordered Silver Nuclei at Picokelvin Temperatures - A Feasibility Study

Risø-M-2874

A.J. Annila,[1] K.N. Clausen,[2] P.J. Hakonen,[1] P.-A. Lindgård,[2] O.V. Lounasmaa,[1] K.K. Nummila,[1] A.S. Oja,[1] K. Siemensmeyer,[3] M. Steiner,[3] J.T. Tuoriniemi,[1] H. Weinfurter,[4] and H.E. Viertiö,[5]

[1] Low Temperature Laboratory, Helsinki University of Technology, SF-02150 Espoo, Finland
[2] Physics Department, Risø National Laboratory, DK-4000 Roskilde, Denmark
[3] Institut für Physik, Johannes Gutenberg Universität, D-6500 Mainz, Federal Republic of Germany
[4] Hahn-Meitner Institut, D-1000 Berlin 39, Federal Republic of Germany
[5] Research Institute for Theoretical Physics, University of Hensinki, SF-00170 Helsinki, Finland

Risø National Laboratory, DK-4000 Roskilde, Denmark
August 1990

Abstract

Nuclear spins in silver constitute an ideal antiferromagnetic spin-$^1/_2$ model system in an fcc lattice. The nuclei are well localized and the interactions coupling the spins can be calculated from first principles. Strong quantum effects are expected owing to spin-$^1/_2$. The magnetic phase diagram of the system has been investigated by several theoretical methods. In the present study the feasibility of neutron diffraction experiments on nuclear magnetic order in silver is discussed. The requirements for cryogenics and for neutron equipment are based on experience with current NMR measurements on silver and with neutron diffraction work on copper. It is concluded that an experiment using an isotopically enriched specimen of either ^{107}Ag or ^{109}Ag is feasible but difficult.

ISBN 87-550-1649-9
ISSN 0418-6435
Grafisk Service Risø 1990.

List of Contents

1. Introduction

The nuclear spin systems in metals provide ideal models to test theoretical ideas by experiments. At low temperatures, an assembly of nuclear spins is effectively isolated from electronic and lattice degrees of freedom. The nuclei are well localized and the interactions between the spins can be calculated from first principles. This has invoked many experimental[1-8] and theoretical[9-19] studies on nuclear magnetism in copper. Neutron diffraction experiments[5,7,8] have made the most essential contribution to the understanding of the ordered state in copper.

The very recent observation of nuclear magnetic ordering in silver by NMR measurements at picokelvin temperatures[20] has inspired us to examine whether this spin system could be studied by means of neutron diffraction as well. Susceptibility measurements, utilizing low frequency ac or NMR techniques, can only give information of the macroscopic properties of the ordered state. Research of the underlying microscopic properties, such as the spin structure of the magnetic ground state, calls for neutron diffraction data.

Natural silver has two isotopes: 51.8% of ^{107}Ag and 48.2% of ^{109}Ag. The magnetic moments of both species are extremely small, $-0.113\,\mu_N$ and $-0.130\,\mu_N$, respectively, where μ_N denotes the nuclear magneton. The nuclear spin is $1/2$ for both isotopes, promising prominent quantum effects. The spins interact via the dipolar force and the conduction-electron-mediated indirect forces. Quadrupolar interactions are absent because of spin-$1/2$. The indirect exchange coupling[11] can be described by the isotropic Ruderman-Kittel interaction.[9] First principle calculations show that this force is strongly nearest neighbour dominated[19] as in copper.[12] In this metal the strengths of the dipolar and the Ruderman-Kittel interactions are comparable, whereas in silver the latter contribution[11] is dominant. Silver is thus a good realization of the nearest neighbour coupled $S=1/2$ antiferromagnetic Heisenberg model in an fcc lattice, the ground state of which has puzzled theorists for decades because of the inherent frustration.[21,22] The problem is that of a system in which there is a high degree of degeneracy of the lowest energy states. Villain et al.[23] have suggested that in this case one may have "ordering by disorder", i.e., the fluctuations, either of quantum or thermal nature, select the ultimate ground state. Another interest-

ing scenario was put forward by Anderson[22] for the S = 1/2 triangular lattice in which a possible new singlet magnetic ground state was proposed. In order to test such ideas it is important to have a system in which the interactions are completely known. The frustration of the AF spin system is due to the fcc structure, and it is essential that no lattice deformations, rearranging the positions, take place. Silver is an ideal model system in this respect as well.

The weak coupling between the nuclear spins and the lattice at submillikelvin temperatures in silver results in a slow spin-lattice relaxation, typically $\tau_1 = 7$ h at 150 μK in zero magnetic field.[20] This makes it possible to study a well isolated nuclear magnetic assembly. Negative absolute temperatures are achievable in practice because the long spin-spin relaxation time, $\tau_2 = 10$ ms[24], permits the inversion of the Zeeman levels.[25,26] This allows a clear experimental demonstration of basic thermodynamic concepts, e.g., an antiferromagnet becomes a ferromagnet at negative temperatures.[27-29]

The neutron diffraction method has been successfully applied to study the nuclear magnetic phase diagram of copper at nanokelvin temperatures.[5-7] The spin dependence of the nucleus-neutron scattering amplitude,[30] which results from the strong interaction, enables investigations similar to those used in electronic magnetism.[31] The long range antiferromagnetic order results in new Bragg peaks, in addition to the ordinary lattice reflections, yielding directly the translational symmetry of the magnetic structure. However, the isotropic nature of the nuclear scattering cross section makes it more difficult to determine the spin directions relative to the lattice. For this purpose, polarized neutrons with full polarization analysis are required. Furthermore, neutron scattering can be used to distinguish true long range order from extensive short range order. The spatial extent of short range correlation can be estimated from the width of the peak.[32]

The work on copper has proved that neutron diffraction is a unique tool for studying metallic nuclear magnets. The propagation vectors of the magnetic structures have been determined. Furthermore, it has been shown that there are different phases, depending on the direction and the strength of the applied external magnetic field. The susceptibility was measured simultaneously with the neutron signal. Besides giving information on whether the

system is in the ordered or paramagnetic state it serves as a tool for other diagnostic purposes as well, e.g., for measuring the high to low field ratio of $\tau_1 T$ and the electronic temperature of the sample. Because of the extremely low energy scale associated with nuclear magnetic systems[4] it has also been possible to study the kinetics of the phase transitions.[8]

1.1. Experimental NMR results on silver

Studies of nuclear magnetism in silver began at Otaniemi in 1986; a sample consisting of polycrystalline silver foils was investigated by NMR measurements. In the first experiments, the NMR absorption spectra of the highly polarized nuclei implied antiferromagnetism.[25] The suppression-enhancement effect of the two isotopic NMR lines[2] was used to determine the sign of the exchange constant. The coupling between the two isotopes was studied in a series of cross relaxation measurements.[33] Experiments at zero field indicated the vicinity of the ordering transition; the susceptibility signal remained nearly constant for about 30 min before an exponential decrease, due to the spin-lattice relaxation, took over. However, similar warmup curves were not observed in every experiment.

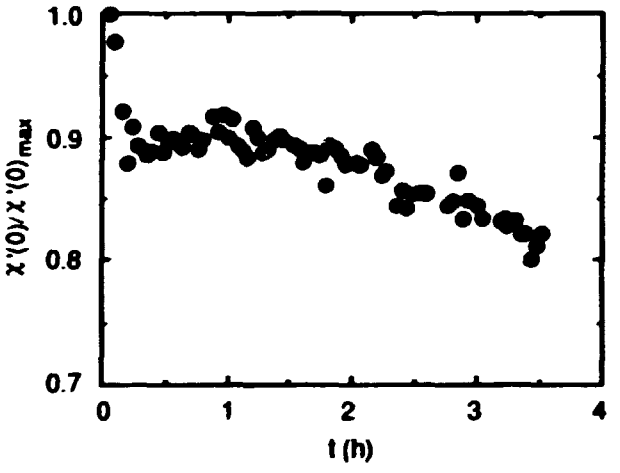

Fig. 1. Static susceptibility $\chi'(0)/\chi'(0)_{max}$ as a function of time t.[20] The characteristic feature of antiferromagnetic order is the increasing signal during the first 45 minutes after the ordered state has been reached at $t \approx 10$ min.

Later, the cooling efficiency of the nuclear demagnetization cryostat was improved and the ordered state was reached reproducibly.[20] A typical signal recorded at zero field as a function of time is shown in Fig. 1. In the ordered state, the susceptibility slowly increases during the first 45 minutes, whereafter spin-lattice relaxation was observed in the paramagnetic phase. The silver nuclei were found to order below $S = 0.53 R \ln 2$ in zero field. In an applied field, $B \cong 40\,\mu T$, the nuclei order below $S = 0.65 R \ln 2$; the critical field $B_c \cong 80\,\mu T$.

The record-low temperature for ordering in silver was found to be 600 pK.[20] Thermometry was based on the thermodynamic relationship $T = \Delta Q/\Delta S$, where ΔS is the measured entropy increase due to an applied heat pulse ΔQ.

Negative temperatures were produced in the nuclear spin system of silver by means of a sudden field reversal, which resulted in inverted populations of the Zeeman levels, and NMR emission spectra were observed. At $T < 0$, the stable spin configuration corresponds to maximum energy at constant entropy, which causes ferromagnetism in silver. The inverse susceptibility, as a function of temperature, obeyed the ferromagnetic Curie-Weiss law $|\chi| = C/(|T| - \theta_F)$, whereas

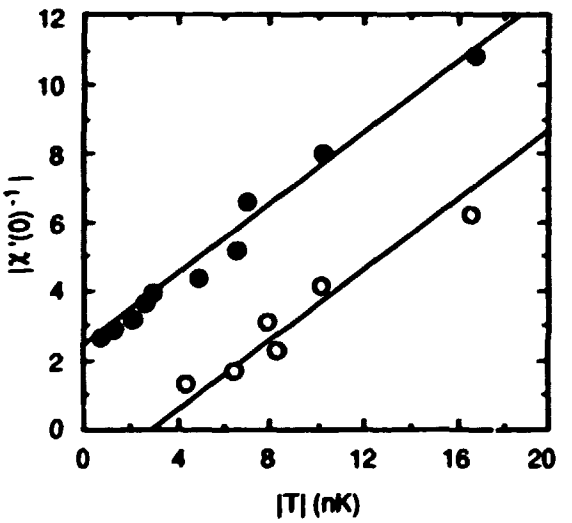

Fig. 2. Absolute value of the inverse static susceptibility $|\chi'(0)^{-1}|$ vs. the absolute value of the temperature measured at $T > 0$ (●) and at $T < 0$ (○).[26]

for $T>0$ the antiferromagnetic law $\chi=C/(T-\theta_A)$ was observed (see Fig. 2); here $C=2.0\,nK$ is the Curie constant, $\theta_F=2.8\,nK$ and $\theta_A=-4.8\,nK$. According to the mean field theory the absolute values of θ_F and θ_A should be equal.

The observed low initial entropy for ordering and the fact that T_c is much lower than $|\theta_A|$ indicate that fluctuations are very important in silver.

1.2. Theoretical predictions

According to the mean field theory, the ground state of the nuclear spin system in silver is continuously degenerate with type-I order.[10] Frustrated antiferromagnets, with competing interactions and nontrivial degeneracies, have evoked considerable interest during recent years.[9-19,21,22,34] The degeneracies are lifted by quantum and thermal fluctuations, higher order interactions and, possibly, by the randomness associated, for example, with two different spin species.

The ground-state spin structure of the silver nuclei has been calculated[14] by spin-wave theory to account for the effects of quantum fluctuations. The diagonalized spin-wave energies give the leading correction to the degenerate ground-state energy. The ordered phases as a function of the external field are shown in Fig. 3. The calculation was restricted to fields in the $(0\bar{1}1)$ plane, which contains the high-symmetry directions [100], [111] and [011]. Simple two-sublattice structures were predicted in almost all field directions and strengths below the critical field B_c. However, in a region around the [011] axis, above $B=B_c/2$, four-sublattice structures were found. Largely similar results were later obtained by second order perturbation theory for a cluster of spins.[15]

The spin configurations have also been investigated by means of Monte-Carlo simulations[16,17] for classical spin systems. It was found that similar phases were selected by thermal fluctuations as well. The stable structures were related to the topological properties of the degenerate ground-state continuum. For silver the critical temperature $T_c=500\,pK$ and the critical field $B_c=140\,\mu T$ were obtained.[17]

However, large quantum fluctuations, expected for the spin 1/2 system, may give rise to a behaviour quite different from the present picture. The Monte-Carlo studies were purely classical, and the other approaches treated the quantum effect as a small perturbation. For very large quantum fluctuations these approximations fail. The observed anomalous behaviour of the phase boundary $T_c(B)$ at low fields[20] is not presently understood. It has been pointed out that there is a similarity between the ground state problem in silver[15] and Anderson's resonating valence-bond model for a triangular lattice.[22] This model proposes a ground state at zero field with no long-range order due to the fluctuating singlet pairing of spins. Such a structure requires a very ideal frustrated system and has not been observed in electronic magnets.

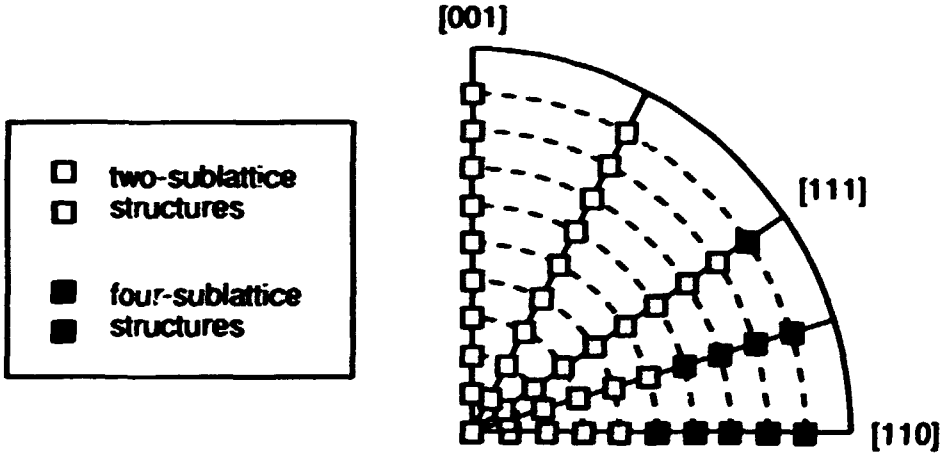

Fig. 3. Phase diagram of nuclear spins in silver at T = 0 as a function of the magnetic field in the (01̄1) plane, calculated by the theory of noninteracting spin waves.[14]

2. Cooling to the ordered state

In the following, technical details of the cryostats employed for research on copper at Risø and on silver in Otaniemi are discussed. The refrigerators are in many respects alike but there are some differences as well. It is important to point out in which respects the equipment at Risø has to be upgraded in order to achieve cryogenic conditions comparable to those in Otaniemi, where ordering experi-

ments on silver have been carried out successfully. Neutron diffraction dictates several important requirements for cryogenics as well.

The entropy and the magnetic field are the most important physical quantities which determine whether or not the ordered state can be reached. The slow spin-lattice relaxation together with the very small magnetic moment of silver makes it difficult to obtain low enough entropy. Furthermore, the small critical field for ordering may unintentionally be exceeded by external remanent fields.

2.1. Entropy considerations

Entropy is extracted from the silver sample by means of a two stage process. Initially, the specimen and the nuclear refrigerant consisting of 21 moles of copper are precooled by a dilution unit to about 12 mK. This will result in a total entropy reduction of a few percent only. The copper refrigerant is then adiabatically demagnetized to 100 - 150 μK. During this phase of the experiment the sample nuclei cool, i.e., heat is being removed by the copper refrigerant from the nuclear spin system of the silver specimen. At these temperatures the rate at which nuclei can be polarized is limited by the spin-lattice relaxation process. Considerable time is needed to reduce the entropy to 0.35Rln2, which is required in order to stay in the ordered state for a reasonable length of time. The corresponding initial nuclear polarization is 87 %.

In a field of 7 T, the entropy is mostly removed at 200 - 400 μK, which requires good thermal contact between the sample and the refrigerant. The copper stage should not warm up substantially, which imposes constraints on the tolerable total heat load coming from the sample and from external sources.

Once a sufficiently low entropy, i.e., high polarization has been obtained, the sample nuclei are demagnetized to the ordered state. Self-heating of the specimen, caused by eddy currents during demagnetization, is of secondary importance under normal circumstances. Since the spin-lattice relaxation time is long, not much of the polarization will be lost, even if the lattice temperature of the sample increases somewhat during the process.

2.1.1. Magnets

High magnetic fields and low temperatures are needed to obtain a sufficiently low entropy in the spin system of the sample prior to demagnetization (see Fig. 4). It is necessary to increase the field vs. temperature ratio currently available at Risø, in order to achieve comparable conditions to those in Otaniemi. In practice, this can be done by raising the field strength. Lowering the temperature of the sample is not feasible because of the long spin-lattice relaxation time.

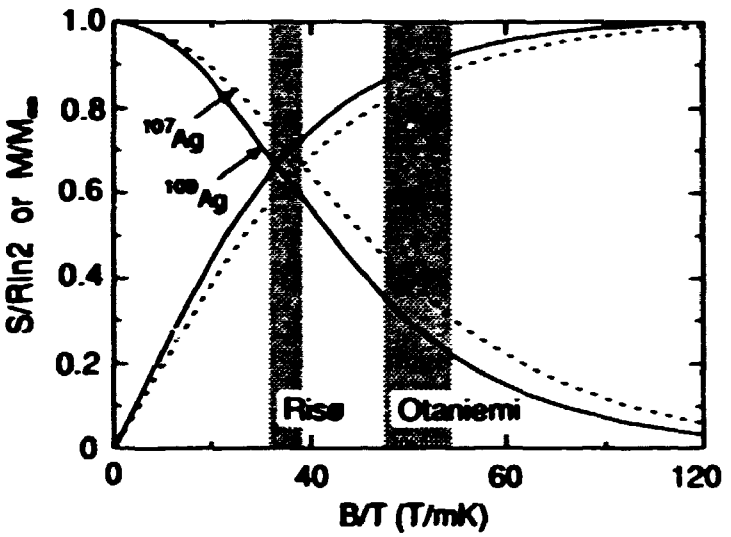

Fig. 4. Entropy and polarization M/M_{sat} in the spin system of silver as functions of the magnetic field/temperature ratio. The experimental conditions achievable at Risø and at Otaniemi are shown as shadowed regions. The widths of the regions are determined by uncertainties in the lattice temperatures.

The required increase in the field strength can be obtained by replacing the existing 4.6 T superconducting sample magnet of the Risø apparatus with a more powerful one. A split-pair coil must be used to allow the neutron beam a free passage to the sample. The split itself does not reduce the field strength much compared to a solenoid. If, however, the thermal link connecting the sample to the refrigerant (see Fig. 5) has a nuclear heat capacity, it is important that the field is excluded from this region. Otherwise, some of the refrigerating capacity is wasted on cooling the thermal link, in addition to the sample.

At the thermal link the field from the main magnet is compensated by an oppositely wound coil. With a split pair magnet it is especially difficult to get both a large and homogeneous field at the sample and compensation at the thermal link (see Fig. 5). As a result of these conflicting requirements, a compromise must be mad9 between the maximum field strength at the sample and the minimum field at the thermal link. Clearly, the designs of the magnet and the thermal link are interconnected.

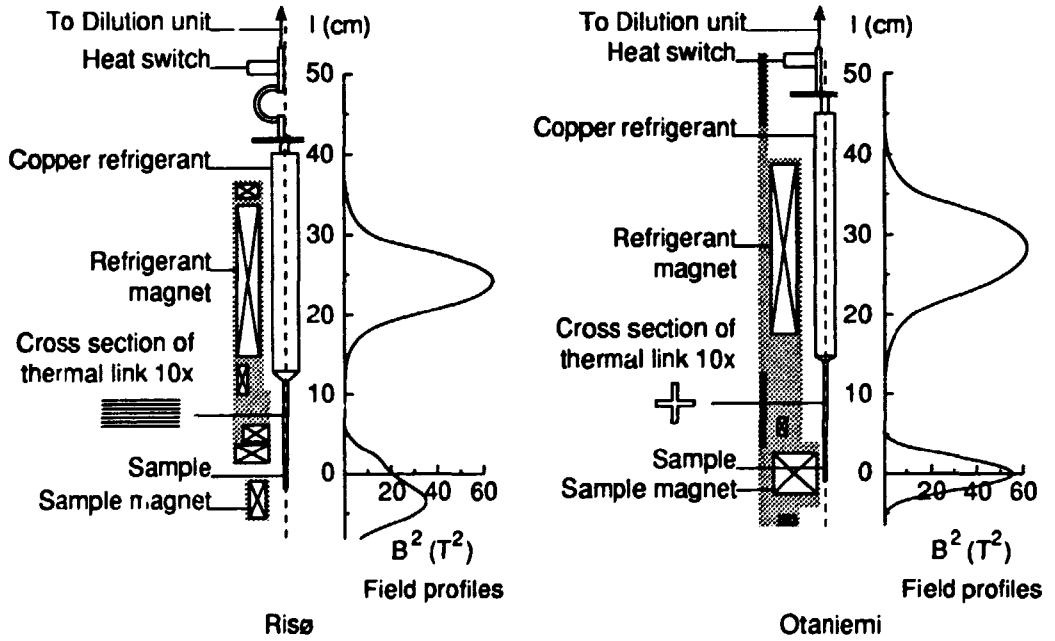

Fig. 5. Schematic drawings of the demagnetization stages in the cryostats at Risø (left) and Otaniemi (right). The cross sections of the magnets and the field profiles are shown with respect to the symmetry axes of the instruments.

In this respect the feasibility of the proposed experiment depends on the field profiles available for split-pair magnets. If it is not possible to have simultaneously a high field at the sample and a sufficiently small field at the thermal link, the cooling capacity of the refrigerant must be increased. At the moment, there are effectively 16 and 21 moles of copper in 8 T field at Risø and Otaniemi, respectively. The cooling capacity of the refrigerant used at Risø might already be marginal. It is estimated that the size can be increased up to 22 moles if the radiation shield for the continuous heat exchanger is removed and the mixing chamber shield is made

larger. Based on the above considerations it is preferable to aim for a new magnet assembly providing a first stage field of 8-10 T and a sample field of 8-9 T generated by a compensated split pair coil.

2.1.2. Thermal link and heat loads

Experience has shown that the quality of the thermal link between the silver sample and the copper refrigerant is of outmost importance. There are many aspects to be considered in its design some of which are conflicting.

The equation relating the lattice temperatures of the sample T_2 and the refrigerant T_1 to the thermal resistance R of the link and to the heat flow $\dot{Q}$ through it is

$$T_2^2 - T_1^2 = 2R\dot{Q}. \qquad (1)$$

It is more efficient to make the product $R\dot{Q}$ smaller rather than to lower T_1 in order to reduce T_2. The link should have a high thermal conductivity since it determines the difference in the lattice temperatures and hence affects the entropy of the sample. The values for the links at Risø and Otaniemi are $R = 10\,K^2/W$ and $30\,K^2/W$, respectively. Selective oxidization at 750-800 °C for 20 h in $1 \cdot 10^{-4}$ Torr of dry air has been found to be a good recipe for neutralizing the magnetic impurities and for improving the quality of the lattice, two factors which determine the thermal resistance.

When the sample cools a considerable heat of magnetization evolves and must be conducted to the copper refrigerant efficiently. The cooling rate of silver nuclei is determined by the spin-lattice relaxation since this is slow compared to the demagnetization rate of the refrigerant. For the sample used in Otaniemi (2 g at 7 T), the calculated total heat of magnetization is 40 μJ. This corresponds to a steady flow of heat at 0.6 nW over 20 hours. If the thermal link has a resistance of $10\,K^2/W$, then a temperature drop of approximately 30-50 μK will develop between the sample and the copper refrigerant at 200-100 μK. This temperature difference becomes even larger in the presence of an external heat leak. Thus, a difference of roughly 50 μK in the electronic temperatures between the sample and the first nuclear stage is unavoidable even in the best case.

A sample in a high magnetic field, at the end of a flexible link, is very susceptible to vibrational heat. Sufficient rigidity of the thermal link will help reduce vibrations which will otherwise cause eddy-current heating. This is of particular significance for neutron diffraction studies since in the guide hall vibrational levels are higher than in usual low temperature laboratory environments. Also, the split-pair magnet tends to increase vibrational heating because its field extends further over the link than that of a compensated solenoid. In Otaniemi the external heat input is 3 - 4 nW with 7.35 T on the second stage magnet and with a 80 mT field over the first nuclear stage. During the copper studies at Risø, vibrational heat leaks on the order of 25 nW at 4.6 T sample field have been measured without effective vibration isolation, and 5 - 10 nW with single passive vibration dampers. Serious efforts should be made to reduce the heat leak at Risø to the same level as in Otaniemi or even below. Vibration dampers in series at critical positions might be sufficient.

The heat capacity of the thermal link must be kept small. In Otaniemi, silver nuclei ordered only after the copper link was replaced by one made of silver. The success resulted because the specific heat, which is proportional to the square of the magnetic moment, is about 300 times smaller for silver than for copper. The heat to be absorbed by the first stage was reduced from 600 μJ to 40 μJ with the link made of silver. It is estimated that in a field generated by a split-pair magnet about 100 μJ have to be removed. Even this is quite small compared with the energy input due to the heat leak, e.g., 5 nW would give 360 μJ in 20 h. Therefore, the amount of silver could well be increased, with only a small increase in the total heat load to the first stage. Only if the background heat leak can be cut down appreciably will a careful minimization of the thermal link's heat capacity be relevant.

Materials with even smaller specific heats and better thermal conductivities than silver are not readily available. A thermal link made of ^{194}Pt, ^{196}Pt, ^{197}Pt, or a mixture of these would probably be the ultimate choice since these isotopes, with natural abundancies of 33%, 25% and 7%, respectively, do not have magnetic moments. However, an isotopically enriched thermal link is expected to be expensive since about 20 grams of the material is needed. If the content of the magnetic isotope ^{195}Pt is reduced below 4%, the heat ca-

pacity of a platinum link becomes smaller than that of a silver link, but the thermal conductivity might decrease due to impurities, because platinum is difficult to purify. On the other hand, a nonmagnetic link would allow a larger sample, a simpler magnet design, higher fields, and a larger effective size of the first nuclear stage because of relaxed requirements for compensating fields.

The cross section of the thermal link can easily be designed so that eddy current heating is small. Traditionally, links have been made of thin foils in order to reduce the diameter of eddy current loops. The cross sections of the links presently employed at Risø and Otaniemi are shown in Fig. 5. A solid silver bar is a good choice with compensated magnets. The improvement in rigidity is obvious. A calculation shows that in the bar eddy current heating is increased by a factor of five during demagnetization, compared to a link made of foils. It is, however, easier to mount the crystal to a bar than to foils. When a stack of foils are diffusion welded to both sides of the sample, the joint can increase the eddy current heating significantly above the calculated value, as was noticed in the copper studies at Risø.

A relatively stiff and bulky thermal link would be the best choice for neutron diffraction studies because a high thermal conductivity and a low vibrational heat leak are more important than low eddy current heating. A platinum link with a vanishingly low heat capacity might be considered if the magnet assembly cannot meet the specifications.

2.2. Remanence problems

The critical field for magnetic ordering is about 80 μT in silver; this may easily be exceeded by various remanent fields in the cryostat. The main source of external fields is the superconducting sample magnet. Additional fields can be generated by magnetic flux trapped to small coils which are used for adjusting the field during experiments. Passive shielding and active compensation can be employed to eliminate remanences. Uniformity of the remanent field at the sample position and a reliable probe for its detection are essential for solving the problem.

2.2.1. Magnetic shielding and compensation

The sample magnets at Risø and Otaniemi have remanent fields of typically ±2 mT and ±1 mT, respectively, when the current terminals are shunted. These fields are due to the rather thick wire used in the magnets.

Shielding is traditionally done by manufacturing the tail section of the vacuum can, surrounding the sample, of μ-metal. The shielding factors obtained this way at Risø, range from 20 to 300. Much better results can be obtained if the shield could be better protected in the cryostat. The μ-metal tube is very susceptible to mechanical stresses and shocks when the cryostat insert is lowered into the magnets. This is a problem at Risø where facilities are not well suited for this particular phase of cryostat mounting, and degradation of the shielding is inevitable. Use of special low-T material, Cryoperm 10 instead of normal μ-metal, should be investigated. In principle the elimination of the remanent field at Risø should not be more difficult than in Otaniemi because the sources of remanences are of comparable size. For convenient regeneration an additional small μ-metal or Cryoperm 10 tube, which may be removed from time to time, should be used. The shielding properties of the μ-metal tail section of the vacuum can at Risø can be restored by heat treatment in a hydrogen atmosphere.

The magnetic flux that might be trapped into the small sample coils which are used to apply the experimental field of desired strength and direction must be taken into account, although it probably does not exceed the critical field of silver. The remanence can be reduced by winding the coils from thin, multifilamentary wire, e.g., $\phi = 50$ μm. The homogeneous remanent field in any direction, resulting from the coils themselves or from the main magnet, can be compensated with three orthogonal coils.

2.2.2. Detection of remanence

A component of the remanent field along an axis of a coil can be detected by susceptibility measurements. For example, by varying the external field stepwise across zero field, the measured susceptibility values fall on a modified Lorenzian curve in the paramagnetic phase.[1] The shift of the curve from zero corresponds to the rema-

nence in that direction (see Fig. 6). In order to find the total remanence, the procedure must be carried out in three orthogonal directions.

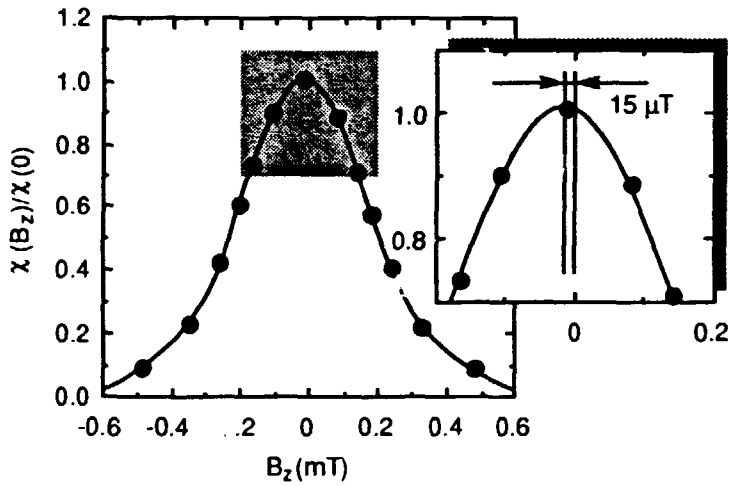

Fig. 6. Detection of the remanent field in copper. The z-componenent is equal to the shift in the center of a symmetric curve fitted through the susceptibility data measured as a function of an applied magnetic field in the z-direction. The x and y components are found in the same way.

In neutron diffraction experiments the field cannot be measured at the position where neutrons hit the sample because hydrogen atoms in the insulation of the wire and in the plastic coil forms would increase the neutron background. This minor problem is easily overcome if the sample coils are made to produce a sufficiently homogeneous field over the specimen and the astatic pickup coil. It is also advantageous, when correcting for demagnetizing fields if the shape of the sample is the same at the position of the pickup coil as in the neutron beam.

The remanence is generally found to be reproducible. Its size can be found by susceptibility measurements in the paramagnetic phase and for a homogenuous field it can be shielded by μ-metal tubes and compensated using three small orthogonal coils.

2.3. Cooling cycle

The need for short cooling cycles is particularly important in neutron diffraction experiments because of the costly beam time. The measurements in Otaniemi are performed once every 72 hours. This time consists of first precooling the refrigerant with the dilution unit for about 44 hours. Demagnetization of the copper stage then takes 3 to 4 hours, and an additional 20 hours are required to achieve sufficient polarization of the sample. The final demagnetization is carried out in less than half an hour and the actual measurements are done within 4 hours. It is obvious that efforts should be concentrated into reducing the longest time intervals.

The low cooling power available at the copper refrigerant, compared to its heat capacity, makes the precooling time long. The cooling power is probably most seriously limited by the heat switch. The zink switch in the Risø cryostat has a thermal resistance of about 40 K^2/W, which is by a factor of ten worse than the values reported for the new Bayreuth cryostat.[35] The switch could be replaced by one made of aluminum with a better mechanical design, but there would also be enough room to accommodate two heat switches working in parallel.

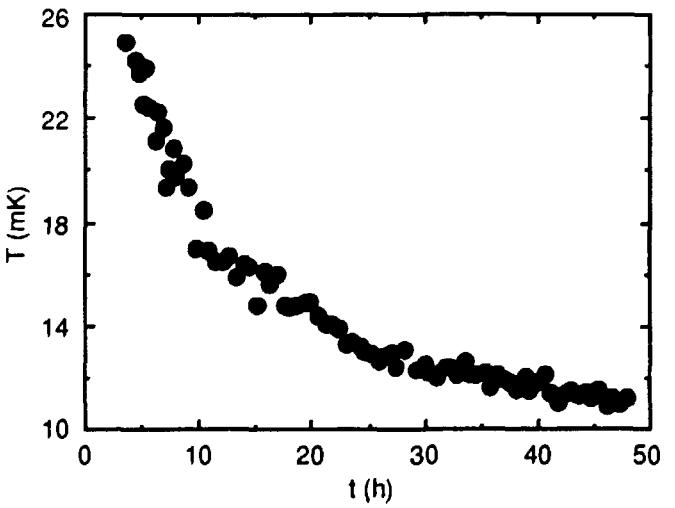

Fig. 7. Temperature of the first nuclear stage at Risø, 16 moles of copper in a 8 T field, as a function of the precooling time.

Since the cooling power of a dilution refrigerator is proportional

to the square of the temperature, it is faster to cool at high temperatures, but stronger magnets would then be required. In Fig. 7 the temperature of the refrigerant is shown for the apparatus at Risø as a function of time during precooling.

The Oxford Model 600 dilution unit of the Risø cryostat is one of the best commercially available machines. It has a nominal cooling power of 4 μW at 10 mK. However, the present pumping facilities do not allow its use with full power. In addition it seems that the pumping line through the 1-K pot is too narrow for effective pumping of the still.

Polarization of the sample is intrinsically slow because of the large Korringa constant $\kappa = \tau_1 T = 10$ sK of silver. As was mentioned earlier, a powerful sample magnet would allow polarization at higher temperatures and, therefore, faster cooling. For example, using a 9 T magnet instead of 7.4 T, the same polarization would be achieved in 16.5 hours instead of 20 hours. A short polarization period would be useful also because in the reactor environment it is difficult to get the heat leak to the nuclear stages below 5 nW. It is estimated that these suggested improvements would shorten the cooling cycle significantly. The helium consumption of the present cryostat at Risø is about 1800 cc/h. The reason for this large boiloff is unknown. The helium consumption quoted by the manufacturer for the dewar and for the magnets are 500 cc/h and 100 cc/h, respectively. This would suggest that the heat leak caused by the insert is unusually large. Proper measurements are needed to pinpoint and correct the cause for the high and expensive boiloff.

The precooling capacity of the present system at Risø should be improved. In particular the new pumping station should have a higher pumping capacity, the 1-K pot should be improved, and the heat switch should be reconstructed or doubled.

3. Ordered state

The two isotopes of silver have important differences in their neutron scattering and absorption properities (see Table 1). Most notably, the spin dependent parts b of the scattering lengths are comparable but of opposite sign. As a result, the nuclear magnetic Bragg reflection from natural silver would be very small. The use of an isotopically enriched sample is thus a necessity. Unfortunately, the absorption cross sections σ_A for both isotopes of silver are large and severe beam heating is expected.

Table 1. Neutron scattering and absorption data of silver.[36,37] For comparison the corresponding numbers are shown for ^{65}Cu. The relative linear absorption length is the linear absorption length μ, measured at wavelength λ_0, divided by λ_0.

	^{107}Ag	^{109}Ag	^{65}Cu
Natural abundancy (%)	51.8	48.2	30.8
Lattice constant a_0 (Å)	4.09	4.09	3.61
Spin I	1/2	1/2	3/2
Scattering length b_0 (fm)	7.55	4.17	10.61
Spin dependent scattering length b (fm)	2.30	-3.70	1.85
$(1/2\ bI)^2$ $(10^{-30}\ m^2)$	0.33	0.86	1.93
Absorption cross section σ_{abs} (barn) at 1.7941 Å	37.6	91.0	2.17
Relative linear absorption length μ/λ_0 (mm/Å)	0.1225	0.2965	0.0103

3.1. Neutron intensity considerations

The scattered intensity $I_M(\tau)$ from a Bragg reflection is proportional to the square of the structure factor $F^2(\tau)$ and depends on the wavelength λ, the scattering angle θ, the neutron transmission $T(\lambda,\ell)$, the number density of silver atoms $N = 4V/a_0^3$, and on the neu-

tron flux $\Phi(\lambda)$ in the following way:

$$I_M(\tau) \propto NF^2(\tau)\lambda^3\Phi(\lambda)T(\lambda,\ell)/\sin(2\theta) \qquad (2)$$

where V is the volume of the sample, a_o is the lattice parameter, and ℓ is the path length for neutrons in the sample.

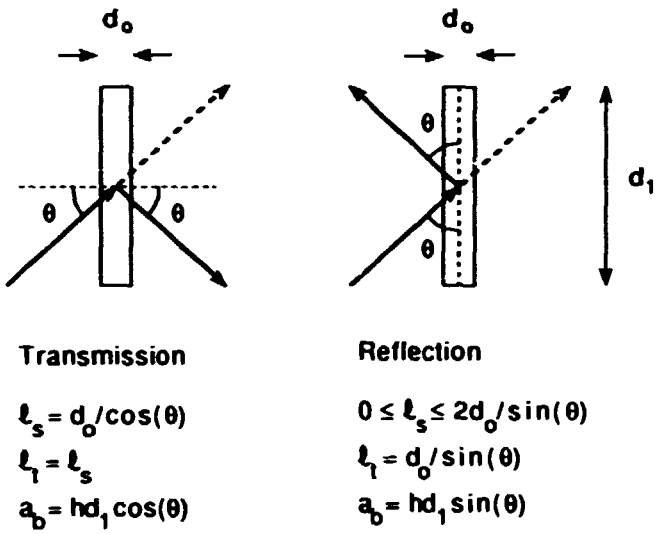

Fig. 8. Path lengths for scattered (ℓ_s) and transmitted (ℓ_t) neutrons in simple transmission and reflection geometries; a_b is the effective area of the sample in the beam.

To estimate the transmission of the scattered beam $T(\lambda,\ell)$, we consider a slab-like sample with dimensions d_o and d_1 in the horizontal plane, height h = 12 mm (as determined by the width of the split in the present magnet) and a (1 0 0) peak in two different geometries, reflection and transmission (see Fig. 8). For the (1 0 0) reflection, $\sin(\theta) = \lambda/(2a_o)$. Since the absorption cross section is much larger than the scattering cross section and extinction is negligible, $T(\lambda,\ell)$ can be calculated for transmission and reflection geometries, respectively, from

$$T_T(\lambda,\ell_s) = \exp(-\ell_s\lambda\mu/\lambda_o) \qquad (3)$$

and

$$T_R(\lambda,\ell_s) = \{1 - \exp[-2d_o\lambda\mu/(\lambda_o\sin(\theta))]\}/[2d_o\lambda\mu/(\lambda_o\sin(\theta))] . \quad (4)$$

The scattering cross section can be written as:

$$|F(\tau)|^2 = \sum_{dd'} \{[b_o^2 + \tfrac{1}{2}b_o b\mathbf{p}(\langle\mathbf{I}_d\rangle + \langle\mathbf{I}_{d'}\rangle) + \tfrac{1}{4}b^2\langle\mathbf{I}_d\rangle\langle\mathbf{I}_{d'}\rangle]\exp[-i\tau(\mathbf{d} - \mathbf{d}')]\} \quad (5)$$

where τ is a reciprocal lattice vector, b_o the spin independent and b the spin dependent part of the neutron-nucleus scattering cross section, $\mathbf{p}$ is the polarization of the neutron beam, $\mathbf{d}$ and $\mathbf{d}'$ are positions in the unit cell, and $\langle\mathbf{I}_d\rangle$ is the thermal average of the nuclear spin at site $\mathbf{d}$.

The first term in Eq. (5) is the usual nuclear structure factor. For the fcc lattice, reflections are observed at reciprocal lattice points with Miller indices (hkl) all even or all odd. The lattice reflections are strong, and sufficient intensity is available to align the sample using the second order contamination of the neutron beam.

The second term in Eq. (5) is generally the largest magnetic contribution to the cross section, but it is only sensitive to the ferromagnetic component and only observable in a polarized beam experiment ($\mathbf{p} \neq 0$). However, a study of nuclear polarization due to an applied magnetic field[6] or caused by ferromagnetic ordering at negative temperatures would require polarized neutrons in order to determine the small nuclear magnetic intensity on top of the lattice signal. Conventional magnetic shielding cannot be used in this case since an unsaturated μ-metal shield will depolarize the neutron beam.

The third term in Eq. (5) is the most important part of the scattering cross section since it contains the antiferromagnetic component. New Bragg reflections with mixed indices will appear if the magnetic unit cell is equal to the fcc unit cell. For larger commensurate magnetic structures, reflections with fractional indices will show up.

In order to estimate the scattered intensity in a silver experiment, the intensity of a nuclear antiferromagnetic (100) peak, with

the same shape and volume for the specimen as in the present ^{65}Cu sample, has been calculated using Eqs. (2 - 5) with the same polarization $\langle I_d \rangle / I$ and the known flux $\Phi(\lambda)$ at the sample position on a cold diffractometer at Risø. The results are shown in Fig. 9.

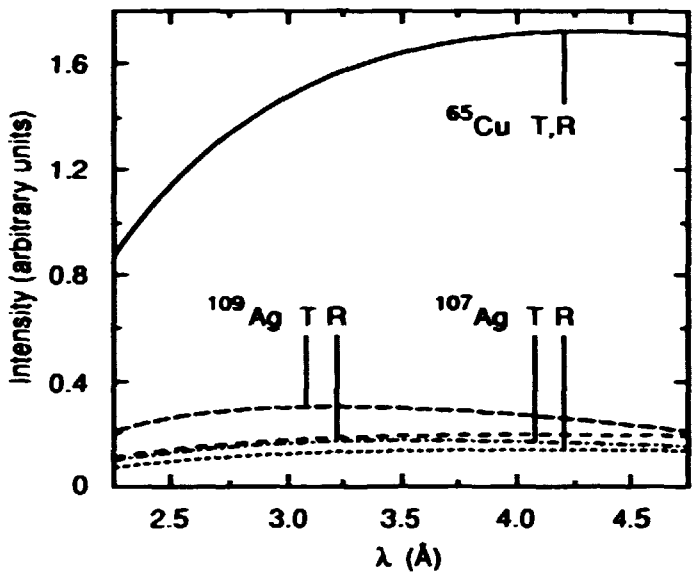

Fig. 9. Estimated intensity for a (1 0 0) nuclear antiferromagnetic Bragg peak of ^{65}Cu, ^{107}Ag, and ^{109}Ag for a sample of dimensions $d_0 = 0.6$ mm, $d_1 = 7$ mm, and $h = 12$ mm; (T) and (R) denote transmission and reflection geometries, respectively.

It is apparent that the intensity expected in a silver experiment is an order of magnitude smaller than for ^{65}Cu. The present copper sample has, however, been slightly bent during mounting, and a photographic inspection of the scattered beam indicates that a sizeable fraction of this crystal does not contribute to the scattering. Since absorption is important in silver, it is not feasible just to increase the sample size. The effect of changing the sample thickness for a fixed height and width is illustrated in Fig. 10. The optimum thickness is 0.5 - 0.6 mm for the enriched ^{109}Ag sample and 1.0 - 1.2 mm for ^{107}Ag. The estimated intensity is about 16% higher for ^{109}Ag, but the thicker ^{107}Ag sample is easier to handle.

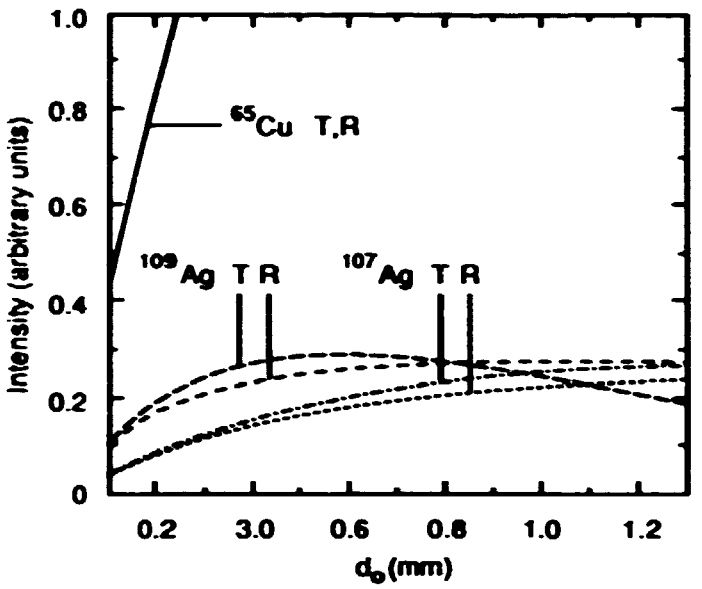

Fig. 10. Estimated intensity of the (1 0 0) peak as a function of slab thickness d_o for transmission (T) and reflection (R) geometries. The height and width of the sample are 12 and 10 mm, respectively. The neutron wavelength is 4.7 Å.

It is equally important to note that the intensity at the magnetic Bragg peak is proportional to the square of the antiferromagnetic

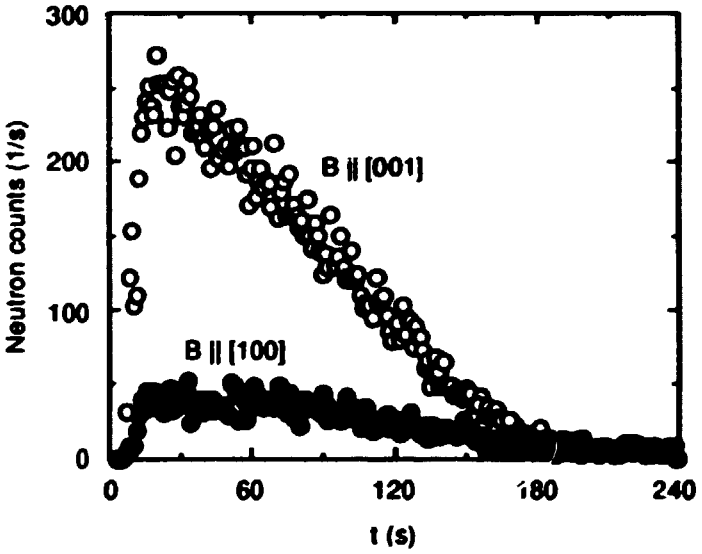

Fig. 11. (100) neutron intensity from a ^{65}Cu crystal as a function of time at B = 0 after the demagnetizations were done along the [001] and the [100] directions with dB/dt = 0.1 mT/s.

sublattice polarization. This is illustrated in Fig. 11 in the case of copper. The (100) neutron intensity at zero field rapidly disappears when the nuclei warm up. Therefore, it is not only the sample size but also how deep into the ordered state the sample can be cooled which determines the integrated intensity of the signal.

It can be seen from Fig. 11 that the time available during the experiment is not sufficient to establish equal populations of the domains in copper. Consequently, it will be useful, already for the preliminary measurements, to be able to choose any field direction in order to observe the most intense domain, i.e., to have a set of three small orthogonal coils for the final demagnetization as in the present setup at Risø.

3.2. Beam heating

The absorption cross sections for both isotopes of silver are much larger than for ^{65}Cu (see Table 1). The sizeable beam heating is a result of neutron capture, followed by prompt γ-emission and subsequent β-decay of the unstable nuclei (see Fig. 12).

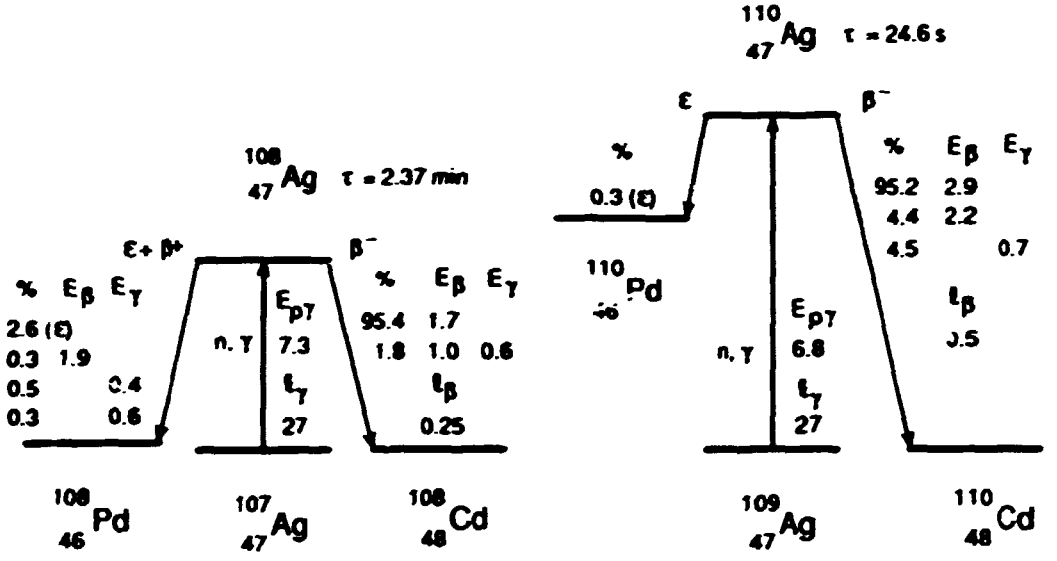

Fig. 12. Schemes for neutron capture of ^{107}Ag and ^{109}Ag and subsequent decay processes of ^{108}Ag and ^{110}Ag. Energies E are expressed in MeV and mean penetration lengths ℓ are given in mm.

Because of the short lifetimes of the exited nuclei, an equilbrium in the beam heating is reached within a few minutes after opening the neutron beam. The beam heating P can be estimated using

$$P = \Phi(\lambda)\, a_b A(\lambda,\ell_t)[\eta_\beta\langle E_\beta\rangle + \eta_\gamma\langle E_{p\gamma}\rangle] \tag{6}$$

where η_β and η_γ are, respectively, the fractions of energy from the β- and γ-radiations which are deposited in the sample (see Fig. 12). The fraction $A(\lambda,\ell_t)$ of neutrons absorbed in the sample is (for absorption much bigger than scattering)

$$A(\lambda,\ell_t) = 1 - \exp(-\ell_t \lambda \mu / \lambda_o) \tag{7}$$

(see Figs. 8 and 12). The quantities η_β and η_γ can be approximated by

$$\eta_\beta = 1 - \exp(-d_o/\langle \ell_\beta \rangle) \tag{8}$$

and

$$\eta_\gamma = 1 - \exp(-d_o/\langle \ell_\gamma \rangle)\ . \tag{9}$$

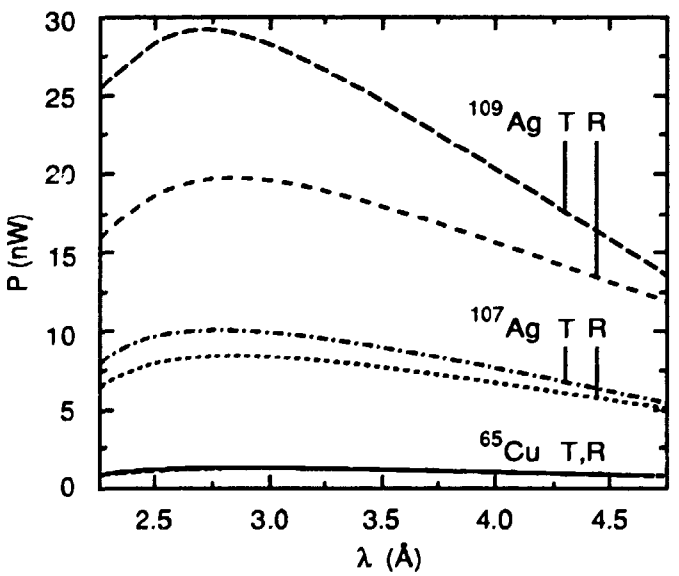

Fig. 13. Estimated beam heating P as a function of wavelength, when observing the (100) peak. The dimensions of the sample are $0.6 \times 7 \times 12$ mm^3. Transmission and reflection geometries are marked by T and R, respectively.

Heating due to β-processes can be reduced if the smallest dimension of the sample is made thin relative to the β-penetration length (ℓ_β). The shape dependence is demonstrated in Fig. 14 for a sample of width 10 mm, height 12 mm, and a wavelength of 4.7 Å. Relative to ^{65}Cu, beam heating in ^{107}Ag and in ^{109}Ag is increased by a factor of 4 - 6 and 9 - 15, respectively.

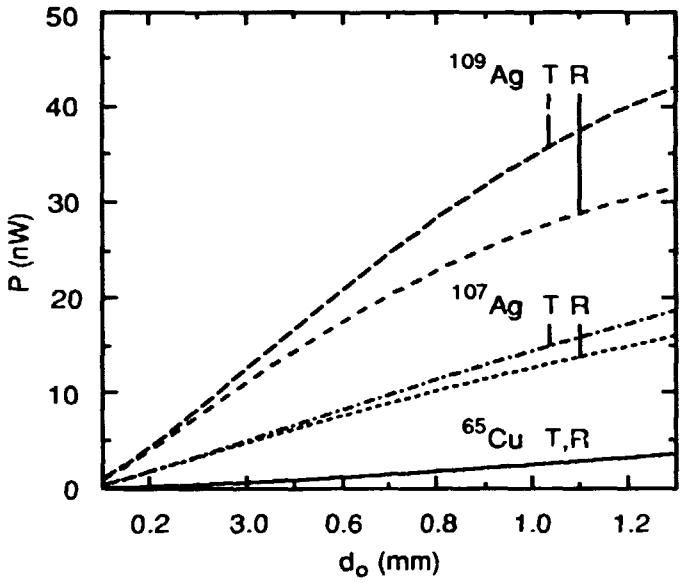

Fig. 14. Estimated beam heating at λ = 4.7 Å for the (100) Bragg peak as a function of the slab thickness d_0 for height 12 mm and width 10 mm. The transmission and reflection geometries are marked with T and R, respectively.

Beam heating reduces the neutron signal in a rather indirect way. The heat is first absorbed by the lattice, whose temperature increase will depend on how effectively the heat is conducted to the copper refrigerant (see Eq. (1)). The higher lattice temperature will, in turn, speed-up the spin-lattice relaxation. This will cause faster nuclear depolarization which results in a decrease of the signal. Solving Eq. (1) for the lattice temperature T_2 of the sample, the spin-lattice relaxation time τ_1 is, according to the Korringa law,

$$\tau_1 = \kappa / T_2 = \kappa / \sqrt{T_1^2 + 2R\dot{Q}} \,. \qquad (10)$$

In Fig. 15 the results of a calculation are shown for an electron temperature of 150 μK in the first nuclear stage and a Korringa constant

$\kappa = 3.8$ sK equal to the zero field value for the Otaniemi sample consisting of natural silver foils.

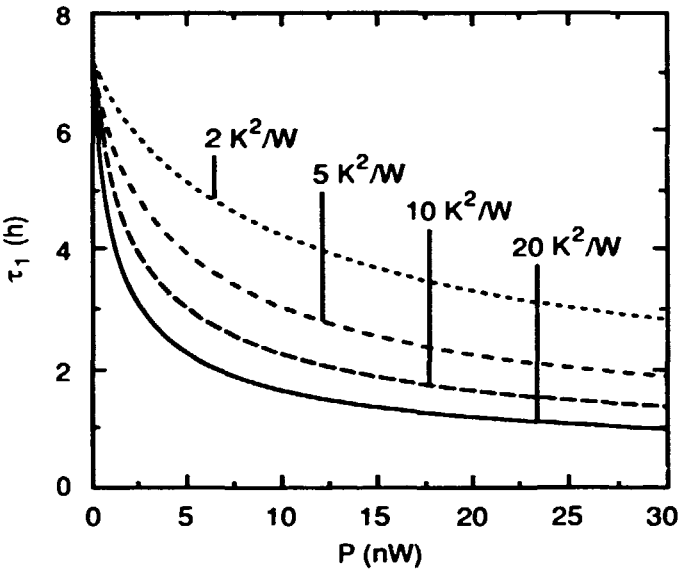

Fig. 15. Calculated spin-lattice relaxation time τ_1 of silver, as a function of the beam heating P, for a few representative values of the thermal resistance R of the link. The Korringa constant $\kappa = 3.8$ sK.

Experience on copper indicates that the magnetic impurity levels of isotopically enriched specimens exceed those in high purity samples of natural composition. As a result, the spin-lattice relaxation time at low fields is shorter than at high fields. It is difficult to estimate the quality of the crystal in this respect beforehand, but the effect is very important. The problem can be overcome to some extent by electrolytically purifying the isotopically enriched sample.

3.3 Comparison of isotopes

The practical sample dimensions for a ^{107}Ag or a ^{109}Ag specimen are $1 \times 10 \times 24$ mm^3 and $0.6 \times 10 \times 24$ mm^3, respectively, with 12 mm of the height in the neutron beam and the rest to be used for susceptibility measurements. The amount of silver in the high field region is then about 2.6 g for ^{107}Ag and 1.6 g for ^{109}Ag. With a neutron wavelength of 4.7 Å, the expected intensities for the two isotopically en-

riched samples are 20% in favour of ^{109}Ag for equal sublattice polarizations. It is, however, expected that higher polarization can be obtained in a ^{109}Ag sample, since it has a larger magnetic moment and a higher T_c than ^{107}Ag. The increase in the intensity due to the larger magnetic moment is estimated (see Fig. 4) to be 5 - 10 % and the ordering temperature should be about 30% higher. Taking the same polarization as for ^{65}Cu, the estimated intensity is approximately a factor of 6 - 7 lower than for the present copper sample.

The estimated beam heating for these specimens are 13 nW and 19 nW, respectively, and the spin lattice relaxation times (see Eq. 10) approximately 2 h and 1.7 h for $\kappa = 3.8$ sK, $T_1 = 150$ μK, and $R = 10\ K^2/W$. The spin lattice relaxation time is approximately six times longer than for the present copper sample, indicating that a silver specimen would stay in the ordered state for approximately 30 min. The expected total number of scattered neutrons per experiment is, therefore, of the same order of magnitude as for copper.

In view of the uncertanties involved in the estimates, the two isotopes appear equally good for the measurements, i.e. the total number of neutrons counted in experiments is expected to be about the same for both of them. Comparison with copper further shows that the experiment, with the modifications pointed out in chapter 2, should be feasible. In order not to set too stringent requirements for the thermal link, one could choose the isotope with a smaller beam heating, i.e. ^{107}Ag; the larger intensity and the smaller sample size, on the other hand, would favour ^{109}Ag. The final selection for the isotope to be used should be based on the realization of the design criteria for the new experimental setup.

3.4. Crystal orientation

The crystal orientation has to be chosen so that the most probable magnetic Bragg reflections are in the scattering plane. Because of the rigid sample mounting, it will be necessary to grow a new crystal if one wishes to change the scattering plane. Theoretical work[14] predicts antiferromagnetic (100) type order in silver. However, there is a local energy minimum at the wavevector $(0\ 3/4\ 3/4)$ which should also be investigated, as well as the $(0\ 2/3\ 2/3)$ reflection found in copper. These constraints fix the scat-

tering plane to $(0\bar{1}1)$ (see Fig. 16). This plane also accomodates reflections of conventional type I, II, and IV antiferromagnetic structures,[38] and all three high symmetry directions in the fcc system.

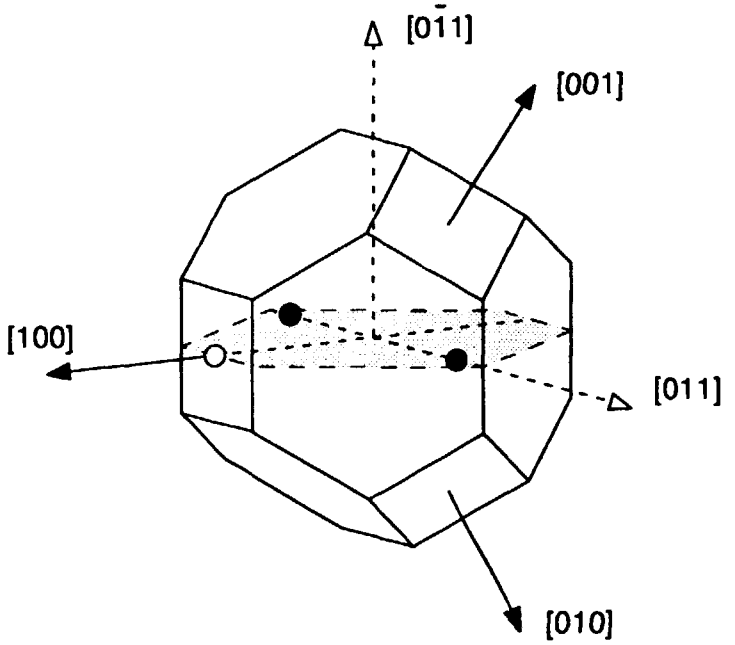

Fig. 16. First Brilluoin zone of an fcc crystal, with the conventional type-I antiferromagnetic reflection (100) (○) and reflections (●) corresponding to a new type of antiferromagnetic order found in copper. The proposed $(0\bar{1}1)$ scattering plane is shaded.

The spectrometer must be able to scan slowly while counting in order to search for eventual new magnetic Bragg reflections. The apparatus should also be equipped with a motorised goniometer and translation for easy positioning and orientation of the sample in the beam.

The crystal should be grown so that the crystallographic [100] and [011] axes coincide with the physical axes of the sample. In this way corrections due to demagnetizing fields are most reliable.

4. Conclusions

The interest in investigating nuclear magnetic ordering in silver by neutron diffraction has arisen recently because of the successful NMR measurements performed in Otaniemi. The silver nuclei were found to order antiferromagnetically at temperatures below 600 pK in magnetic fields below 80 μT. The nuclear spin system in silver is a good realization of the $S = 1/2$ antiferromagnetic Heisenberg model in the fcc lattice, whose ground state has been extensively studied but still remains an unsolved problem in magnetism. A neutron diffraction experiment would provide direct information on the ordered phase(s) and the ordering vector(s) of the structure(s). Furthermore, phase transitions can be studied, and it might be feasible to investigate whether the zero field phase is characterized by extended short range order, which is a plausible candidate for the structure of the frustrated $S = 1/2$ fcc antiferromagnet.

A similar neutron diffraction experiment has been carried out on copper at Risø. The nuclear magnetic phase diagram was determined at nanokelvin temperatures. In this report we have studied the feasibility of a neutron diffraction experiment on silver and pointed out the necessary modifications to the present experimental system in order to reach conditions comparable to those in Otaniemi, where nuclear ordering in silver has been observed.

To ensure an adequate cooling capacity, a new magnet assembly is needed. A more powerful sample magnet (8 - 9 T) is required to achieve a sufficiently low entropy of the silver nuclei, which is a prerequisite for the ordering. It would allow the removal of the entropy at higher temperatures, thus shortening the intrinsically long time needed for the polarization of the sample. A stronger magnet for the first nuclear stage (10 T) would also help to reduce the cooling cycle and to provide a sufficient thermal reservoir to absorb the external heat leaks, beam heating, and the heat of magnetization of the sample. For a further reduction of the cooling cycle, modifications allowing full exploitation of the cooling power of the dilution refrigerator should be made. This makes improvements in the heat switch necessary.

The thermal resistance of the link connecting the sample to the copper refrigerant should be smaller or at least equal to the present

value corresponding to $R = 10\ K^2/W$, in order to achieve sufficient nuclear polarization during a shorter cooling cycle and to conduct the sizeable beam heating away during the experiment. The external heat leak, at present mainly due to vibrations, should be reduced below 5 nW by improving the vibration isolation. Compensation for the field at the thermal link could be relaxed if necessary. The additional heat capacity would be dominant only at very low external heat leaks, $\dot{Q} < 1$ nW.

An isotopically enriched sample must be used because the spin dependent scattering cross sections for the two stable isotopes of silver are comparable but of opposite sign. As a result, very small intensity would be expected from natural silver where the two isotopes are nearly equally abundant. Experience on copper indicates that the magnetic impurity levels of the isotopically enriched samples are higher than those in specimens of natural composition. This will result in shorter measuring times than otherwise expected. The selection of a specific isotope for the sample is an intricate question, and the best candidate will depend on how well the design criteria for the new setup can be fulfilled.

With the setup and facilities described above, a neutron diffraction study of nuclear magnetic order in silver appears to be challenging and difficult, but feasible.

Acknowledgements

A.J.A and J.T.T are indebted to the Finnish Cultural Foundation for scholarships. J.T.T acknowledges support by the Academy of Finland.

References

1. G.J. Ehnholm J.P. Ekström, J.F. Jacquinot, M.T. Loponen, O.V. Lounasmaa, and J.K. Soini, Phys. Rev. Lett. **42**, 1702 (1979).
2. J.P. Ekström, J.F. Jacquinot, M.T. Loponen, J.K. Soini, and P. Kumar, Physica **98B**, 45 (1979).
3. M.T. Huiku, T.A. Jyrkkiö, J.M. Kyynäräinen, A.S. Oja, and O.V. Lounasmaa, Phys. Rev. Lett. **53**, 1692 (1984).
4. Recent reviews: A.S. Oja, Physica Scripta **T19**, 462 (1987), and O.V. Lounasmaa, Phys. Today **42**, 26 (1990).
5. T.A. Jyrkkiö, M.T. Huiku, O.V. Lounasmaa, K. Siemensmeyer, K. Kakurai, M. Steiner, K.N. Clausen, and J.K. Kjems, Phys. Rev. Lett. **60**, 2418 (1988).
6. T.A. Jyrkkiö, M.T. Huiku, K.N. Clausen, K. Siemensmeyer, K. Kakurai, and M. Steiner, Z. Phys. B **71**, 139 (1988).
7. A.J. Annila, K.N. Clausen, P.-A. Lindgård, O.V. Lounasmaa, A.S. Oja, K. Siemensmeyer, M. Steiner, J.T. Tuoriniemi, and H. Weinfurter, Phys. Rev. Lett. **64**, 1421 (1990).
8. A.J. Annila, K.N. Clausen, A.S. Oja, K. Siemensmeyer, M. Steiner, J.T. Tuoriniemi, and H. Weinfurter, Physica B (1990), submitted.
9. M.A. Ruderman and C. Kittel, Phys. Rev. **96**, 99 (1954).
10. L.H. Kjäldman and J. Kurkijärvi, Phys. Lett. **71A**, 454 (1979).
11. A.S. Oja and P. Kumar, J. Low Temp. Phys. **66**, 155 (1987).
12. P.-A. Lindgård, X.-W. Wang, and B.N. Harmon, J. Magn. & Magn. Mater. **54-57**, 1052 (1986).
13. S.J. Frisken and D.J. Miller, Phys. Rev. Lett. **57**, 2971 (1986).
14. H.E. Viertiö and A.S. Oja, Phys. Rev. B **36**, 3805 (1987).
15. P.-A. Lindgård, Phys. Rev. Lett. **61**, 629 (1988), and to be published.
16. S.J. Frisken and D.J. Miller, Phys. Rev. Lett. **61**, 1017 (1988).
17. H.E. Viertiö and A.S. Oja, *Quantum Fluids and Solids*, edited by G.G. Ihas and Y. Takano, AIP Conference Proceedings No.**194**, 305 (1989), and H.E. Viertiö, Physica Scripta (1990), to be published.
18. H.E. Viertiö and A.S. Oja (1990), to be published.
19. H.E. Viertiö, A.S. Oja, X.-W. Wang, and B.N. Harmon (1990), to be published.
20. P.J. Hakonen, S. Yin, and K.K. Nummila, to be published.

21. D. ter Haar and M. Lines, Phil. Trans. Roy. Soc. London **A 254**, 521 (1962), and ibid. **255**, 1 (1962).
22. P.W. Anderson, Mater. Res. Bull. **8**, 153 (1973).
23. J. Villain, R. Bidaux, J.-P. Cartons, and R. Conte, J. Physique **41**, 1263 (1986).
24. A. Narath, A.T. Fromhold, Jr., and E.D. Jones, Phys. Rev. **144**, 428 (1966).
25. A.S. Oja, A.J. Annila, and Y. Takano, to be published.
26. P.J. Hakonen, S. Yin, and O.V. Lounasmaa, Phys. Rev. Lett. **64**, 2707 (1990).
27. A. Abragam, *The Principles of Nuclear Magnetism*, Chapter V, and references therein (Clarendon Press, Oxford, 1961).
28. M. Goldman, J. Magn. & Magn. Mater. **14**, 105 (1979).
29. A. Abragam and M. Goldman, in *Nuclear Magnetism: Order and Disorder* (Clarendon Press, Oxford,1982).
30. H. Glättli and M. Goldman, *Neutron Scattering*, edited by K. Sköld and D.L. Price, Methods of Experimental Physics **23C**, 241 (Academic Press, New York, 1987).
31. M. Steiner, Physica Scripta (1990), in press.
32. *Neutron Scattering*, edited by K. Sköld and D.L. Price, Methods of Experimental Physics **23A-C** (Academic Press, New York, 1987).
33. A.S. Oja, A.J. Annila, and Y. Takano, Phys. Rev. Lett. (1990), submitted.
34. C.L. Henley, Phys. Rev. Lett. **62**, 2056 (1989).
35. F. Pobell, personal communication.
36. V.F. Sears, AECL-report 8490, Chalk River (1984).
37. H. Glättli, G.L. Bacchella, M. Fourmond, A. Malinovski, P. Mériel, M. Pinot, P. Roubeau, and A. Abragam, J. Physique **7**, 629 (1979).
38. P.J. Brown, Physica **137B**, 31 (1986).

Risø National Laboratory **Risø – M – 2874**

Title and author(s)

NEUTRON DIFFRACTION EXPERIMENTS ON ORDERED SILVER NUCLEI AT PICOKELVIN TEMPERATURES - A FEASIBILITY STUDY

A.J. Annila, K.N. Clausen, P.J. Hakonen, P.-A. Lindgård, O.V. Lounasmaa, K.K. Nummila, A.S. Oja, K. Siemensmeyer, M. Steiner, J.T. Tuoriniemi, H. Weinfurter and H.E. Viertiö

Date August 1990

Department or group

Physics

Groups own registration number(s)

Project/contract no.

Pages 36 **Tables** 1 **Illustrations** 16 **References** 38

ISBN 87-550-1649-9

Abstract (Max. 2000 char.)

Nuclear spins in silver constitute an ideal antiferromagnetic spin - ½ model system in an fcc lattice. The nuclei are well localized and the interactions coupling the spins can be calculated from first principles. Strong quantum effects are expected owing to spin - ½. The magnetic phase diagram of the system has been investigated by several theoretical methods. In the present study the feasibility of neutron diffraction experiments on nuclear magnetic order in silver is discussed. The requirements for cryogenics and for neutron equipment are based on experience with current NMR measurements on silver and with neutron diffraction work on copper. It is concluded that an experiment using an isotopically enriched specimen of either ^{107}Ag or ^{109}Ag is feasible but difficult.

Descriptors – INIS

COPPER; CRYOSTATS; FEASIBILITY STUDIES; NEUTRON DIFFRACTION; NUCLEAR MAGNETIC RESONANCE; NUCLEAR MAGNETISM; SILVER; SILVER 107; SILVER 109; SPIN ORIENTATION

Available on request from Risø Library, Risø National Laboratory, (Risø Bibliotek, Forskningscenter Risø), P.O. Box 49, DK-4000 Roskilde, Denmark.

Telephone 42 37 12 12, ext. 2268/2269. Telex: 43116, Telefax: 46 75 56 27

P405000099/89

Available on exchange from:
Risø Library,
Risø National Laboratory, P.O. Box 49,
DK-4000 Roskilde, Denmark
Phone +45 42 37 12 12, ext. 2268/2269
Telex 43 116, Telefax +45 46 75 56 27

ISBN 87-550-1649-9
ISSN 0418-6435